

# The HII region G35.673-00.847: another case of triggered star formation?

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## ABSTRACT

**Aims.** As part of a systematic study that we are performing with the aim to increase the observational evidence of triggered star formation in the surroundings of HII regions, we analyze the ISM around the HII region G35.673-00.847, a poorly studied source.

**Methods.** Using data from large-scale surveys: Two Micron All Sky Survey, Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE), MIPS GAL, Galactic Ring Survey (GRS), VLA Galactic Plane Survey (VGPS), and NRAO VLA Sky Survey (NVSS) we performed a multiwavelength study of G35.673-00.847 and its surroundings.

**Results.** The mid IR emission, shows that G35.673-00.847 has an almost semi-ring like shape with a cut towards the galactic west. The radius of this semi-ring is about 1'5 ( $\sim 1.6$  pc, at the distance of  $\sim 3.7$  kpc). The distance was estimated from an HI absorption study and from the analysis of the molecular gas. Indeed, we find a molecular shell composed by several clumps distributed around the HII region, suggesting that its expansion is collecting the surrounding material. We find several YSO candidates over the molecular shell. Finally, comparing the HII region dynamical age and the fragmentation time of the molecular shell, we discard the collect and collapse as the mechanism responsible for the YSOs formation, suggesting other processes such as radiative driven implosion and/or small-scale Jeans gravitational instabilities.

**Key words.** ISM: HII regions – ISM: clouds – stars: formation

## 1. Introduction

During the last years, the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) performed with data obtained from the *Spitzer Space Telescope*, was a very useful tool to study the Galactic IR emission with unprecedented quality and resolution, and still remains so. Using these mid-IR data, for instance, it is possible to clearly identify the photodissociation regions (PDRs) surrounding HII regions. Thus, from a multiwavelength analysis can be studied the interaction between the HII region and the surrounding interstellar medium (ISM), and eventually discover triggered star formation. One of the triggered processes recently largely studied in the HII region

borders is the “collect and collapse”, which was early proposed by Elmegreen & Lada (1977). In such process, during the supersonic expansion of an HII region, a dense layer of material can be collected between the ionization and the shock fronts. This layer can be fragmented in massive condensations that then can collapse to lead the formation of new massive stars and/or clusters. Recent observational studies support that this mechanism is taking place in several HII regions (see e.g. Petriella et al. 2010; Pomarès et al. 2009; Zavagno et al. 2007, and references therein).

G35.673-00.847 (hereafter G35.6) is an HII region poorly studied. The source was cataloged in the HII region catalogue of Lockman (1989), who obtained a recombination line at  $v_{\text{LSR}} \sim 60 \text{ km s}^{-1}$ . According to the IRAS catalogue of Point Sources, G35.6 coincides with the source IRAS 18569+0159. In the NRAO VLA Sky Survey (NVSS), Condon et al. (1998) identified two radio sources: NVSS 185929+020334 and 185938+020012 towards this region.

This work is part of a systematic study that we are performing with the aim to increase the observational evidence of triggered star formation in the surroundings of HII regions. We present a molecular and near- and mid-IR study of the environment that surrounds the HII region G35.6 with the purpose of exploring the ISM around it, and looking for signatures of star formation.

## 2. Data

We analyzed data extracted from four large-scale surveys: Two Micron All Sky Survey (2MASS)<sup>1</sup>, Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE), MIPS GAL and GRS<sup>2</sup>.

GLIMPSE is a mid infrared survey of the inner Galaxy performed using the *Spitzer Space Telescope*. We used the mosaicked images from GLIMPSE and the GLIMPSE Point-Source Catalog (GPSC) in the *Spitzer*-IRAC (3.6, 4.5, 5.8 and 8  $\mu\text{m}$ ). IRAC has an angular resolution between 1''5 and 1''9 (see Fazio et al. 2004 and Werner et al. 2004). MIPS GAL is a survey of the same region as GLIMPSE, using MIPS instrument (24 and 70  $\mu\text{m}$ ) on *Spitzer*. The MIPS GAL resolution at 24  $\mu\text{m}$  is 6''.

The GRS was performed by the Boston University and the Five College Radio Astronomy Observatory (FCRAO). The survey maps the Galactic Ring in the  $^{13}\text{CO}$  J=1–0 line with an angular and spectral resolution of 46'' and  $0.2 \text{ km s}^{-1}$ , respectively (see Jackson et al. 2006). The observations were performed in both position-switching and On-The-Fly mapping modes, achieving an angular sampling of 22''.

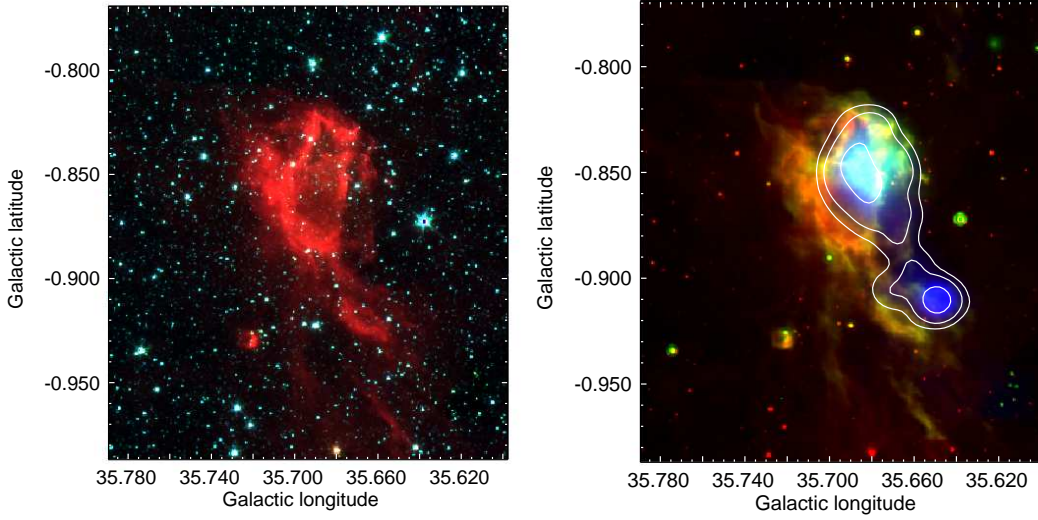
Additionally we used HI data with an angular resolution of  $\sim 1'$  extracted from the VLA Galactic Plane Survey (VGPS; Stil et al. 2006) and radio continuum data extracted from the NRAO VLA Sky Survey (NVSS) with an angular resolution of  $\sim 45''$  (Condon et al. 1998).

## 3. Presentation of G35.673-00.847 (G35.6)

Figure 1 shows two composite three color images of G35.6. The left image displays three *Spitzer*-IRAC bands: 3.6  $\mu\text{m}$  (in blue), 4.5  $\mu\text{m}$  (in green) and 8  $\mu\text{m}$  (in red). The right image shows the *Spitzer*-IRAC emission at 8  $\mu\text{m}$  (in red), the *Spitzer*-MIPSGAL emission at 24  $\mu\text{m}$  (in green) and

<sup>1</sup> 2MASS is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

<sup>2</sup> Galactic Ring Survey (Jackson et al. 2006)

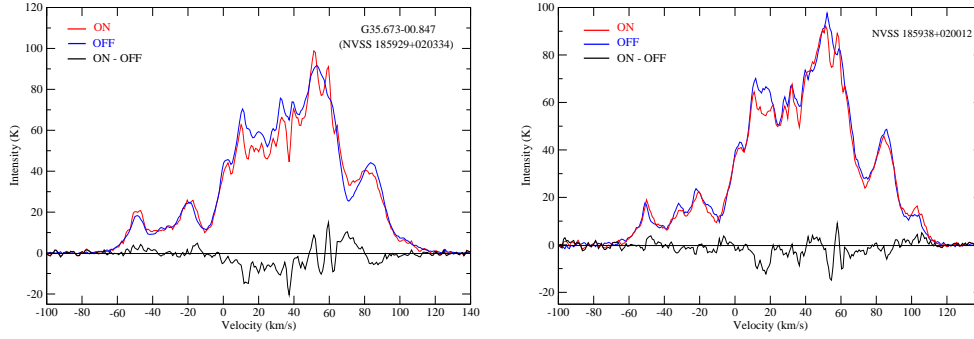


**Fig. 1.** Left: *Spitzer*-IRAC three color image ( $3.6 \mu\text{m}$  = blue,  $4.5 \mu\text{m}$  = green and  $8 \mu\text{m}$  = red). Right: color composite image where the *Spitzer*-IRAC  $8 \mu\text{m}$  emission is displayed in red, the *Spitzer*-MIPSGAL emission at  $24 \mu\text{m}$  in green, and the NVSS radio continuum emission at  $20 \text{ cm}$  is presented in blue and emphasized with white contours with levels of  $2.5$ ,  $6$  and  $20 \text{ mJy beam}^{-1}$ . The  $\sigma_{\text{rms}}$  of the NVSS data is  $0.45 \text{ mJy beam}^{-1}$ .

the NVSS radio continuum emission at  $20 \text{ cm}$  (in blue and emphasized with white contours). Both figures clearly show the PDR visible in the  $8 \mu\text{m}$  emission, which is mainly originated in the polycyclic aromatic hydrocarbons (PAHs). The PAHs emission delineates the HII region boundaries because these large molecules are destroyed inside the ionized region, but are excited in the PDR by the radiation leaking from the HII region (Pomarès et al. 2009). The  $24 \mu\text{m}$  emission reveals the presence of hot dust, and the radio continuum emission shows two sources, one related to G35.6, probably due to its ionized gas, and other lying towards the south. Both sources are: NVSS 185929+020334 and 185938+020012, respectively (Condon et al. 1998). The PAH emission shows that G35.6 has an almost semi-ring like shape with a cut towards the galactic west. The radius of this semi-ring is about  $1'.5$ . Extending towards the south is visible another PDR, which can be related to the radio continuum source NVSS 185938+020012. On the other hand, a little bubble is present in the field, at  $l = 35^\circ 722$ ,  $b = -0^\circ 928$ . The emission at  $8 \mu\text{m}$  and  $24 \mu\text{m}$ , showing the presence of PAH and hot dust towards this bubble, suggest that it could be a young HII region.

#### 4. Distance

G35.6 presents a radio recombination line at  $v_{\text{LSR}} \sim 60 \text{ km s}^{-1}$  (Lockman 1989), which, by applying the flat galactic rotation curve of Fich et al. (1989), that assumes circular rotation around the galactic center, gives the possible kinematic distances of  $\sim 4.0$  or  $\sim 9.8 \text{ kpc}$ . This ambiguity arises because we are studying a region in the first galactic quadrant, where a given velocity may be associated with two possible distances. Using HI data we performed an absorption study towards the radio sources G35.6 (NVSS 185929+020334) and NVSS 185938+020012. Figure 2 shows the HI spectra towards both sources. The HI emission obtained over the source (the On position: a beam over the radio maximum of the source) is presented in red, in blue is presented the average HI emission taken from four positions separated by approximately a beam from the source in direction of the four galactic cardinal points (the Off position), and the subtraction between them is presented

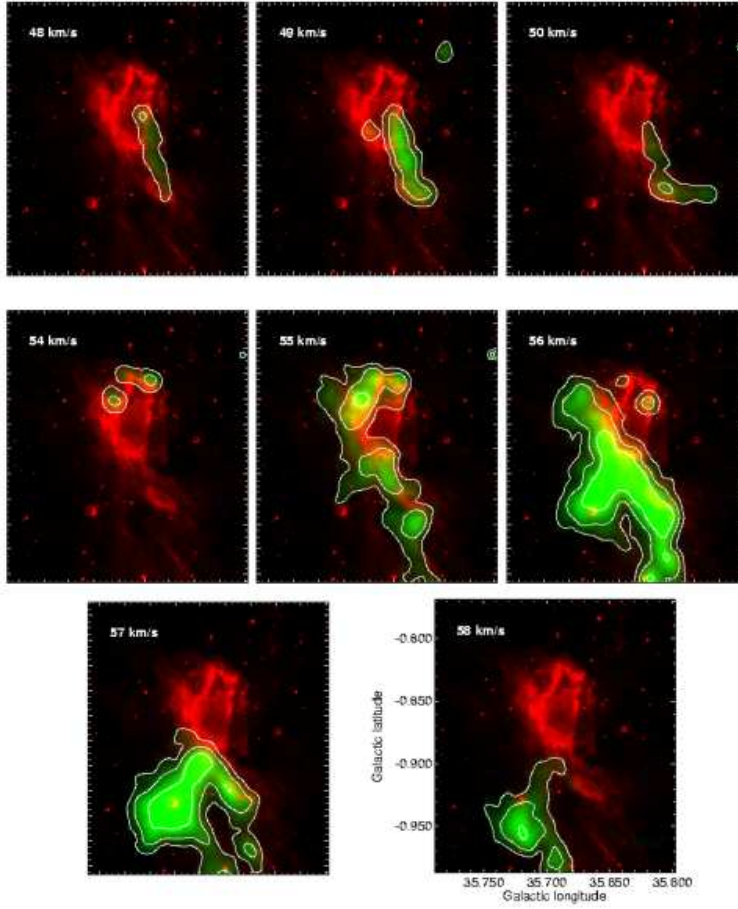


**Fig. 2.** Left: HI spectra obtained towards the source G35.6 (NVSS 185929+020334). Right: HI spectra obtained towards the source NVSS 185938+020012. The spectra obtained towards the sources (the On position) are presented in red, in blue is presented the averaged HI emission taken from four positions separated by approximately a beam from the source in direction of the four galactic cardinal points (the Off position), and the subtractions between them are presented in black. The  $3\sigma$  uncertainty of the subtraction is  $\sim 10$  K.

in black, which has a  $3\sigma$  uncertainty of  $\sim 10$  K. The figure shows that both sources have similar HI absorption features, suggesting that they are located at the same distance. The last absorption feature appears at  $v \sim 61 \text{ km s}^{-1}$ , in coincidence with the G35.6 recombination line (Lockman 1989). Taking into account that the tangent point (at  $v \sim 89.7 \text{ km s}^{-1}$ ) does not present any absorption, following Kolpak et al. (2003), we favour the near kinematic distance.

## 5. Molecular analysis

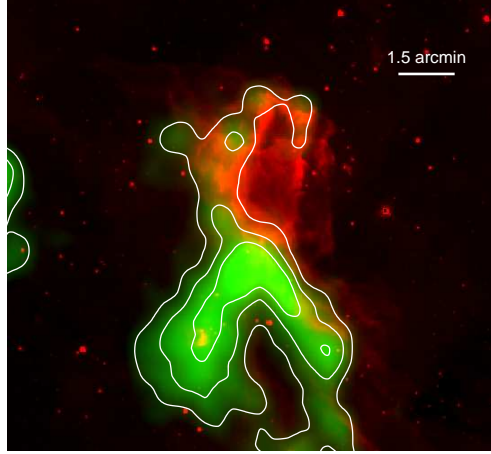
We analyze the whole  $^{13}\text{CO}$   $J=1-0$  data cube and we find some interesting molecular structures between 47 and  $60 \text{ km s}^{-1}$ . Figure 3 displays the integrated velocity channel maps of the  $^{13}\text{CO}$   $J=1-0$  emission every  $\sim 1 \text{ km s}^{-1}$ , showing the kinematical and morphological structure of a molecular cloud probably related to the HII region G35.6. Between  $\sim 48$  and  $51 \text{ km s}^{-1}$  appears a molecular structure delineating the PDR that extends to the south. No molecular gas is observed between 51 and  $54 \text{ km s}^{-1}$  (this velocity interval is not shown in Fig. 3). Finally, between 54 and  $59 \text{ km s}^{-1}$  appear several molecular clumps distributed over the borders of G35.6 and the southern PDR, which may indicate that the collect and collapse process could be taking place in this region. As Deharveng et al. (2005) point out, the presence of a dense molecular shell surrounding the ionized gas of an HII region, or the presence of massive fragments regularly spaced along the ionization front, can prove that we are dealing with the collect and collapse mechanism. Figure 4 shows the  $^{13}\text{CO}$   $J=1-0$  emission integrated between 53 and  $61 \text{ km s}^{-1}$  (in green) over the  $8 \mu\text{m}$  emission (in red). The very good correspondence between the eastern HII region border, traced by the IR emission, and the molecular gas, strongly suggests that the observed molecular shell has been swept and shaped by the expansion of G35.6. The central velocity of the molecular gas is  $\sim 57 \text{ km s}^{-1}$ , which gives the possible kinematic distances of 3.7 or 10.1 kpc. According to the study presented in Sec. 4, we favour the nearest one. Taking into account that the ionized gas may be moving away from the molecular material, we use the central velocity of the molecular gas to adopt 3.7 kpc as the distance of the whole complex.



**Fig. 3.** Integrated velocity channel maps of the  $^{13}\text{CO}$  J=1–0 emission (in green) every  $\sim 1 \text{ km s}^{-1}$  in two velocity intervals: from  $\sim 48$  to  $51 \text{ km s}^{-1}$  (shown in the first three panels) and from  $\sim 54$  to  $59 \text{ km s}^{-1}$  (shown in the remaining panels). The contour levels of the  $^{13}\text{CO}$  J=1–0 emission are 1, 2 and  $4 \text{ K km s}^{-1}$ . Red is the  $8 \mu\text{m}$  emission.

In order to have an estimate of the mass and density of the described molecular shell, we assume LTE, an excitation temperature of 20 K, a distance of 3.7 kpc, and that the  $^{13}\text{CO}$  emission is optically thin. From the standard LTE equations, we obtain a  $N(^{13}\text{CO}) \sim 3 \times 10^{16} \text{ cm}^{-2}$ , and using the relation  $N(\text{H}_2)/N(^{13}\text{CO}) \sim 5 \times 10^5$  (e.g. Simon et al. 2001), we obtain a molecular mass and a density of  $\sim 1.5 \times 10^4 M_\odot$  and  $\sim 1 \times 10^4 \text{ cm}^{-3}$ , respectively. The integration was performed over all the observed positions within the  $4.5 \text{ K km s}^{-1}$  contour level shown in Fig. 4, following the shell geometry shown at the  $55 \text{ km s}^{-1}$  channel map in Fig. 3, i.e., the molecular condensation extending towards the southeast was not considered. To calculate the volume of the molecular shell, we assume a length along the line of sight of  $\sim 1'$  ( $\sim 1.1 \text{ pc}$  at the distance of 3.7 kpc), which is approximately the average of the shell width seen in the plane of the sky (see the  $55 \text{ km s}^{-1}$  channel map in Fig. 3). On the other hand, it is important to note that the little bubble described in Sec. 3, probably a young HII region, is likely embedded in this molecular condensation, suggesting to be active in star formation.





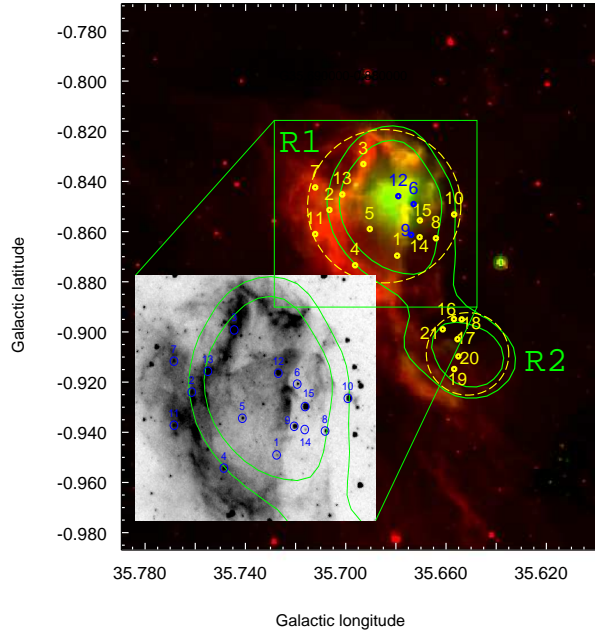
**Fig. 4.**  $^{13}\text{CO}$  J=1–0 emission (in green) integrated between 53 and 61  $\text{km s}^{-1}$ . The contour levels of the  $^{13}\text{CO}$  J=1–0 emission are 4.5, 8 and 12  $\text{K km s}^{-1}$ . Red is the 8  $\mu\text{m}$  emission.

## 6. Exciting stars

No exciting star of the HII region G35.6 was found in the literature. In this work, we give some indirect evidence suggesting the possible location and properties of the exciting star(s) of the region.

The first piece of information is given by the radio continuum emission of G35.6, which allow us to derive the expected spectral type of the exciting star. The number of UV ionizing photons needed to keep an HII region ionized is given by  $N_{\text{uv}} = 0.76 \times 10^{47} T_4^{-0.45} \nu_{\text{GHz}}^{0.1} S_{\nu} D_{\text{kpc}}^2$  (Chaisson 1976), where  $T_4$  is the electron temperature in units of  $10^4$  K,  $D_{\text{kpc}}$  the distance in kpc,  $\nu_{\text{GHz}}$  the frequency in GHz, and  $S_{\nu}$  the measured total flux density in Jy. Assuming an electron temperature of  $T = 10^4$  K, a distance of 3.7 kpc, and using a total flux density of 0.86 Jy at 2.7 GHz for G35.6 (Reich et al. 1984) and a total flux density of 0.053 Jy at 1.4 GHz for NVSS 185938+020012 (Condon et al. 1998), the total amount of ionizing photons needed to keep these sources ionized turns out to be about  $N_{\text{uv}} = 1.0 \times 10^{48} \text{ ph s}^{-1}$  and  $N_{\text{uv}} = 0.6 \times 10^{47} \text{ ph s}^{-1}$ , respectively. It is well established that part of the UV radiation can be dissipated in heating the dust. In fact, Inoue (2001) and Inoue et al. (2001) demonstrated that typically only half of the Lyman continuum photons from the central source in a Galactic HII region ionizes neutral hydrogen, and the rest are absorbed by dust grains within the ionized region. Taking this into account, considering errors of about ten percent in the distance and in the radio continuum flux at 2.7 GHz, and based on the ionizing fluxes for massive stars given by Martins et al. (2005), the estimated spectral type of the ionizing star of G35.6 ranges between O7.5V and O9V.

Additionally we perform a photometric study of the infrared point sources in the region based on the GLIMPSE I Spring'07 and the 2MASS All-Sky Point Source Catalogs. Only sources with detections in the four *Spitzer*-IRAC bands and in the three 2MASS bands were considered. We find 30 and 8 sources towards the HII region G35.6 (R1 in Fig. 5) and towards the source NVSS 185938+020012 (R2 in Fig. 5), respectively. To examine the evolutionary stage of the infrared point sources, we analyze their location onto a color-color IRAC diagram. Following Allen et al. (2004) color criteria, we found 15 and 6 sources in R1 and R2, respectively, that can be classified as main sequence stars (Class III). Table 1 presents these sources with its 2MASS designation (Col. 2), apparent *JHK* magnitudes (Cols. 3-5), estimated extinctions (Col. 6), calculated absolute *JHK* magnitudes (Cols. 7-9) and when its derived spectral type coincides with an O-type star is remarked



**Fig. 5.** *Spitzer*-IRAC two color image ( $8\ \mu\text{m}$  = red and  $24\ \mu\text{m}$  = green). The green contours represent the radio continuum emission at 20 cm. The crosses show the location of the main sequence star candidates in R1 and R2 (dashed circles).

in Col. 10. The errors in the estimated extinctions and in the calculated absolute  $JHK$  magnitudes are below 20% and 30%, respectively. The sources are labeled according to Fig. 5, which displays their location into a two color image, where the  $8\ \mu\text{m}$  and  $24\ \mu\text{m}$  emissions are displayed in red and green, respectively. The green contours delineate the radio continuum emission at 20 cm. To look for O-type stars (likely responsables of ionizing the surrounding gas), we use the  $J$ ,  $H$ , and  $K$  apparent magnitudes obtained from the 2MASS Point Source Catalog to derive the absolute  $JHK$  magnitudes. To perform that, we assume a distance of about 3.7 kpc and we obtain the extinction for each source from the  $(J-H)$  and  $(H-K)$  colors. We assume the interstellar reddening law of Rieke & Lebofsky (1985) ( $A_J/A_V=0.282$ ;  $A_H/A_V=0.175$  and  $A_K/A_V=0.112$ ) and the intrinsic colors  $(J-H)_0$  and  $(H-K)_0$  obtained from Martins & Plez (2006). By comparing the derived absolute magnitudes with those tabulated by Martins & Plez (2006), we find that seven sources in Region 1, #2, #4, #5, #6, #11, #12, #14, and five sources in Region 2, #16, #17, #18, #19 and #20, have absolute  $JHK$  magnitudes that are in agreement with an O-type star (see Table 1).

Finally, taking into account that the exciting star candidates are expected to be in a PAHs hole, we discard sources #2, #4 and #11 as the responsible of generate G35.6. The rest of the exciting star candidates, sources #5, #6, #12 and #14 are located in projection inside the radio continuum and  $24\ \mu\text{m}$  emissions; among them, sources #6 and #12 are located close to the maximum of the  $24\ \mu\text{m}$  emission as could be expectable for an exciting star. On the other hand, as can be seen in Figure 5, source #6, is located into a hole of the  $5.8\ \mu\text{m}$  emission (see zoom of the region in the figure). It is well known that the exciting star(s) of an HII region generate a cavity of dust and gas through the action of the radiation pressure on the dust grains (Gail & Sedlmayr 1979), which suggests that source #6 is the more likely candidate to be the exciting star of G35.6. On the other hand, using the same assumptions that in R1, we found that based on the radio continuum flux at 1.4 GHz in R2,

**Table 1.** Exciting star candidates in regions R1 and R2. The sources number correspond to the numeration in Fig. 5.

#	2MASS Designation	<i>J</i>	<i>H</i>	<i>K</i>	<i>A<sub>v</sub></i>	<i>M<sub>J</sub></i>	<i>M<sub>H</sub></i>	<i>M<sub>K</sub></i>	O-type star
<i>R1</i>									
1	J18593297+0202530	11.92	11.52	11.40	4.18	-2.10	-2.05	-1.91	-
2	J18593204+0204495	16.67	13.34	11.69	30.26	-4.70	-4.80	-4.54	yes
3	J18592664+0204362	13.90	10.54	8.86	30.61	-7.58	-7.66	-7.41	-
4	J18593563+0203404	15.05	12.25	10.88	25.44	-4.97	-5.05	-4.81	yes
5	J18593189+0203454	14.66	12.11	11.01	22.12	-4.42	-4.60	-4.31	yes
6	J18592786+0203057	14.14	11.88	10.92	19.58	-4.23	-4.39	-4.11	yes
7	J18593076+0205225	11.11	10.60	10.52	4.31	-2.95	-2.99	-2.80	-
8	J18592979+0202149	13.35	11.05	10.05	20.17	-5.18	-5.32	-5.05	-
9	J18593057+0202486	13.28	10.70	9.53	22.81	-6.00	-6.13	-5.87	-
10	J18592697+0202073	12.66	10.11	8.89	23.09	-6.69	-6.77	-6.53	-
11	J18593472+0204518	16.34	13.32	11.88	27.07	-4.13	-4.26	-3.99	yes
12	J18592785+0203304	11.69	10.30	9.56	13.83	-5.05	-4.96	-4.83	yes
13	J18593016+0204431	13.84	10.65	8.90	30.39	-7.57	-7.51	-7.35	-
14	J18593041+0202363	14.38	12.47	11.64	16.95	-3.24	-3.34	-3.10	yes
15	J18592897+0202470	11.54	9.09	7.87	22.60	-7.67	-7.71	-7.50	-
<i>R2</i>									
16	J18593584+0200579	14.35	12.37	11.51	17.50	-3.43	-3.53	-3.29	yes
17	J18593743+0200411	14.07	11.69	10.58	21.40	-4.81	-4.90	-4.66	yes
18	J18593556+0200488	13.81	11.97	11.25	15.70	-3.46	-3.62	-3.35	yes
19	J18594015+0200255	15.76	12.94	11.67	24.73	-4.06	-4.23	-3.94	yes
20	J18593887+0200288	15.20	12.82	11.71	21.40	-3.68	-3.77	-3.53	yes
21	J18593725+0201066	15.22	13.21	12.25	18.47	-2.83	-2.86	-2.66	-

the exciting stars of NVSS 185938+020012 would be later than an O9.5V star. The later spectral type stars found in R2 could be sources #16 and #18.

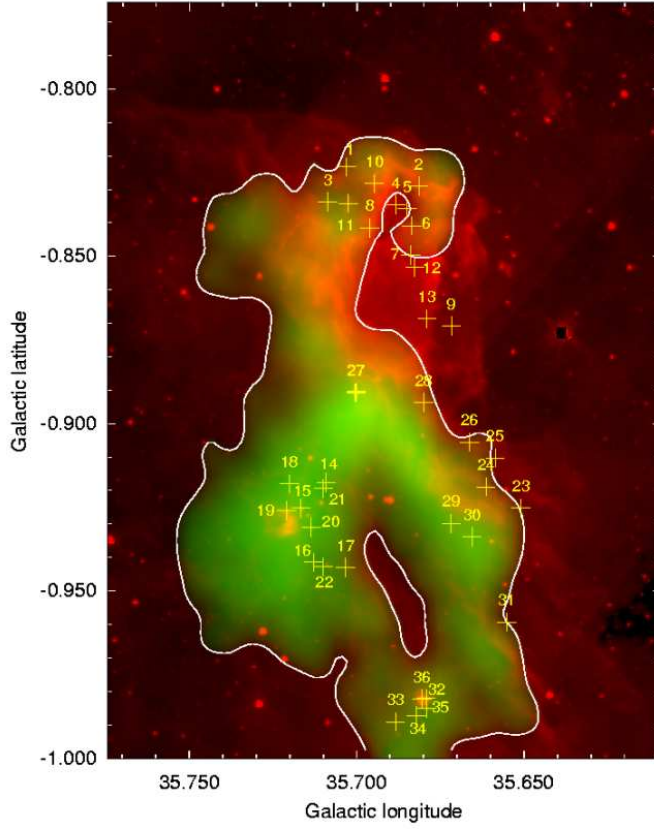
It would be very useful to have UBV fluxes to perform a better photometry in order to identify without doubt the exciting stars, however it is very difficult to obtain these fluxes because of the interstellar absorption towards this region in the Galaxy.

## 7. Star Formation

In Sec. 5 we show that the HII region G35.6 is evolving and affecting a molecular cloud, presenting an excellent scenario to probe triggered star formation. In this section we look for young stellar objects (YSOs) around G35.6. YSOs are generally classified according to their evolutionary stage: class I are the youngest sources, embedded in dense envelopes of gas and dust, and class II are sources whose emission is originated mainly in the accretion disk around the central protostar. In both cases, a YSO will show an infrared excess that cannot be attributed to the scattering and absorption of the ISM along the line of sight. On the contrary, this infrared excess is mainly due to the presence of the envelope and/or the disk of dust around the central protostar. In other words, YSOs are intrinsically red sources.

Robitaille et al. (2008) defined a color criterion to identify intrinsically red sources using data from the *Spitzer*-IRAC bands. Intrinsically red sources satisfy the condition  $m_{4.5} - m_{8.0} \geq 1$ , where  $m_{4.5}$  and  $m_{8.0}$  are the magnitudes in the 4.5 and 8.0  $\mu\text{m}$  bands, respectively. On the other hand, an





**Fig. 6.** Two-color image: the  $^{13}\text{CO}$  emission integrated between 53 and 61  $\text{km s}^{-1}$  is presented in green, and the 8  $\mu\text{m}$  emission, in red. For a better contrast, the  $^{13}\text{CO}$  emission scale is displayed in square root and bordered by a white contour. The yellow crosses indicate the position of the intrinsically red sources, i.e. sources satisfying the condition  $m_{4.5} - m_{8.0} + \varepsilon \geq 1$ . We labeled the sources that appear to be related with the molecular gas around G35.6.

externally reddened source is a source not intrinsically red (such as main sequence stars) which appears red because of the interstellar effects. They satisfy the condition  $m_{4.5} - m_{8.0} < 1$  and their spectral energy distributions (SEDs) are well fitted by stellar photosphere models with interstellar extinction. In order to consider the errors in the magnitudes, we use the following color criterion to select intrinsically red sources:  $m_{4.5} - m_{8.0} + \varepsilon \geq 1$ , where  $\varepsilon = \sqrt{(\Delta_{4.5})^2 + (\Delta_{8.0})^2}$  and  $\Delta_{4.5}$  and  $\Delta_{8.0}$  are the errors of the 4.5 and 8.0  $\mu\text{m}$  bands, respectively. On Fig. 6 we show the distribution of the sources extracted from the GLIMPSE catalog around G35.6 that satisfy the previous criterion (we only considered sources with detections in both 4.5 and 8.0  $\mu\text{m}$  bands). The intrinsically red sources are distributed into four groups. The first group (Group 1) is found towards the north and includes sources 1 to 13. A second group (Group 2) of sources is located over the southeastern molecular structure. This portion of the molecular cloud is far from G35.6 and probably is not being perturbed by the HII region. Sources 23, 24, 25, 26, 29 and 30 form Group 3 which appears in the molecular gas likely associated with the border of the radio continuum source NVSS 185938+020012. Then, we identify a fourth group (Group 4) towards the southern portion of the molecular cloud, far from the HII regions. And finally, sources 27, 28 and 31 that are not part of any group. Sources 27 and 28, taking into account their position, could be related to G35.6 southern border. On Table 2 we report the fluxes of the intrinsically red sources in the 2MASS and *Spitzer*-IRAC bands, specifying

**Table 2.** Near- and mid-IR fluxes of the sources satisfying the condition  $m_{4.5} - m_{8.0} + \varepsilon \geq 1$  around G35.6.

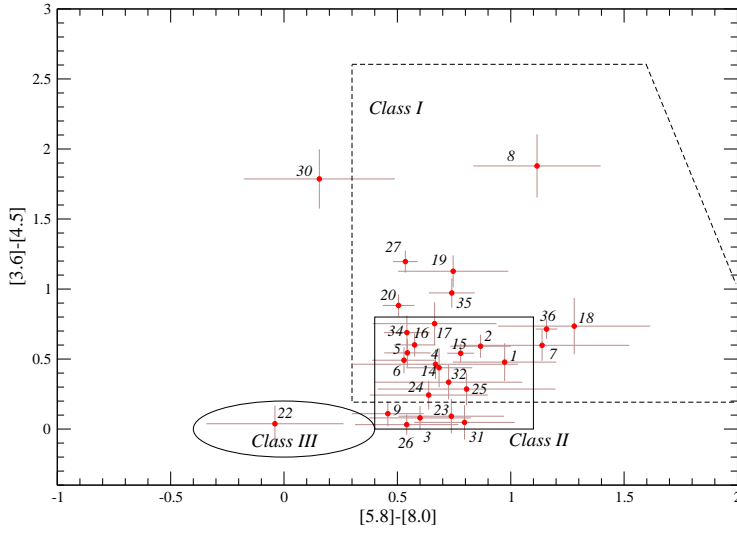
The numbers of the YSO candidates correspond to the numeration in Fig. 6

Source	GLIMPSE Desig.	2MASS Qual.	$J$ (mag)	$H$ (mag)	$K_S$ (mag)	$3.6\ \mu\text{m}$ (mag)	$4.5\ \mu\text{m}$ (mag)	$5.8\ \mu\text{m}$ (mag)	$8.0\ \mu\text{m}$ (mag)	$24\ \mu\text{m}$ (Jy)
YSO 1	G035.7031-00.8232	BAA	16.513	14.154	12.967	12.086	11.603	11.258	10.285	
YSO 2	G035.6814-00.8290	AAA	15.830	13.625	12.495	11.284	10.692	10.049	9.182	
YSO 3	G035.7086-00.8337	BAA	16.641	13.712	12.405	11.423	11.343	10.609	10.009	
YSO 4	G035.6882-00.8346	UUA	18.264	15.119	14.434	12.445	11.992	11.545	10.877	
YSO 5	G035.6850-00.8358	UAA	17.304	15.046	13.740	12.101	11.557	11.057	10.513	
YSO 6	G035.6836-00.8409	UAE	18.038	15.025	13.485	11.546	11.054	10.487	9.958	
YSO 7	G035.6838-00.8496	UAA	17.579	15.185	14.077	12.942	12.344	12.307	11.169	
YSO 8	G035.6961-00.8415	N/A				13.176	11.297	9.674	8.558	0.14
YSO 9	G035.6716-00.8708	AAA	15.493	13.459	12.624	11.955	11.845	11.431	10.973	
YSO 10	G035.6947-00.8282	N/A				13.616	13.762		9.994	
YSO 11	G035.7025-00.8342	N/A				14.065	13.908		9.828	
YSO 12	G035.6826-00.8533	N/A				14.114	13.431		10.776	
YSO 13	G035.6790-00.8687	N/A				13.970	13.690		10.811	
YSO 14	G035.7094-00.9176	N/A				13.583	13.145	11.983	11.299	
YSO 15	G035.7166-00.9252	AAA	15.776	13.607	12.112	10.110	9.568	8.992	8.213	0.05
YSO 16	G035.7127-00.9414	AAA	15.713	14.113	13.148	11.797	11.196	10.718	10.142	
YSO 17	G035.7032-00.9430	N/A				13.242	12.489	11.977	11.313	
YSO 18	G035.7201-00.9180	N/A				14.267	15.532	12.876	11.596	
YSO 19	G035.7209-00.9260	UAA	18.218	14.992	13.379	10.983	9.856	9.109	8.363	0.16
YSO 20	G035.7135-00.9309	UUA	18.257	16.988	13.519	11.184	10.301	9.740	9.235	0.05
YSO 21	G035.7099-00.9193	N/A					13.787	12.354	11.781	0.03
YSO 22	G035.7103-00.9428	UAA	16.441	14.637	13.419	12.754	12.716	11.904	11.944	
YSO 23	G035.6509-00.9252	AAA	15.825	13.779	12.688	12.018	11.926	11.673	10.935	
YSO 24	G035.6613-00.9189	UAA	17.288	14.442	13.061	12.238	11.995	11.687	11.049	
YSO 25	G035.6585-00.9103	UAA	18.328	15.205	13.736	12.791	12.505	12.328	11.523	
YSO 26	G035.6663-00.9055	UAA	17.509	13.978	12.464	11.240	11.208	10.885	10.344	
YSO 27	G035.7002-00.8907	UUA	14.254	12.706	13.451	10.951	9.755	8.856	8.321	0.14
YSO 28	G035.6799-00.8936	UAA	17.204	15.356	14.118	13.152	12.933		10.466	
YSO 29	G035.6717-00.9298	N/A				13.379	12.823		11.280	
YSO 30	G035.6655-00.9338	N/A				14.952	13.166	11.493	11.337	0.04
YSO 31	G035.6551-00.9593	AAA	16.315	14.103	13.002	12.365	12.317	12.050	11.254	
YSO 32	G035.6791-00.9821	UAA	15.364	14.161	12.039	10.210	9.916	9.250	8.524	
YSO 33	G035.6883-00.9891	BAA	16.607	14.877	14.225	13.284	13.150		11.873	
YSO 34	G035.6820-00.9873	UAA	17.289	14.683	13.584	11.714	11.025	10.649	10.107	
YSO 35	G035.6790-00.9851	UUB	18.284	15.686	14.581	11.914	10.942	10.260	9.520	
YSO 36	G035.6804-00.9823	UAA	14.186	11.459	9.535	7.425	6.711	5.985	4.827	

**Notes.** 2MASS Qual.: A and B are the best photometric qualities, with a SNR  $\leq 10$  and  $\leq 7$ , respectively. E means that the source magnitude is questionable. And U means that the magnitude value is an upper limit.

the GLIMPSE designation (Col. 2) and the 2MASS photometric quality (Col. 3). In the case of sources 8, 15, 19, 20, 21, 27, and 30, we obtained their fluxes at  $24\ \mu\text{m}$  from the MIPS image and are presented in Col. 11 of the table.

So far we have identified the intrinsically red sources located right upon the molecular gas around the HII region G35.6. However, according to Robitaille et al. (2008) intrinsically red sources may include YSOs, planetary nebulae (PNe), galaxies, AGNs, and AGB stars. We must apply an



**Fig. 7.** Color-color diagram  $[5.8]-[8.0]$  versus  $[3.6]-[4.5]$  for sources of Table 2 with detections in the four *Spitzer*-IRAC bands. The regions indicate the stellar evolutionary stage based on the photometric criteria of Allen et al. (2004).

additional constraint to these sources in order to discern their real nature. Regarding extragalactic sources, Robitaille et al. (2008) pointed out that at most 0.4% of the intrinsically red sources selected by the color criterion  $m_{4.5} - m_{8.0} > 1$  are galaxies and AGNs. So, there is a little probability to find an extragalactic source in our short sample of red sources. Concerning to AGB stars, we look in catalogues for these stars. In the region analyzed in this work there are not any AGB star catalogued. To look for YSOs and PNe candidates we constructed a color-color (CC) diagram  $[5.8]-[8.0]$  versus  $[3.6]-[4.5]$  with the sources from Table 2 that have flux detections in the four *Spitzer*-IRAC bands. We used the photometric criteria of Allen et al. (2004) to identify class I and II YSOs (Fig. 7). From its positions in this color-color diagram we find that only source 22 cannot be classified as a class I or II YSO. Source 30 falls outside the class I region but if we take into account the errors in the fluxes we should consider it as a YSO candidate. On the other hand, sources 7 and 18 are found in the CC diagram close to the location of PNe, which typically have  $[5.8]-[8.0] > 1.4$  (Cohen et al. 2007). However, we will consider them as YSO candidates too.

Finally, we fitted the spectral energy distribution (SED) of the sources from which we obtained fluxes at  $24 \mu\text{m}$  from the MIPS image using the tool developed by Robitaille et al. (2007) and available online<sup>3</sup>. We assume an interstellar absorption between 12 and 22 mag. These values were obtained from the 2MASS  $J-H$  versus  $H-K_s$  color-color diagram (not presented here) constructed with the sources with the best photometric quality (AAA) within a circle of  $8'$  in radius centered at G35.6. The lower value is compatible with the expected extinction towards star forming regions which, according to Neckel & Klare (1980), is generally greater than 10 magnitudes. The upper value is in agreement with the visual absorption of  $A_v \sim 20$  mag obtained from  $A_v = 5 \times 10^{-22} N(H)$  (Bohlin et al. 1978), where  $N(H) = N(HI) + 2N(H_2)$  is the line-of-sight hydrogen column density

<sup>3</sup> <http://caravan.astro.wisc.edu/protostars/>

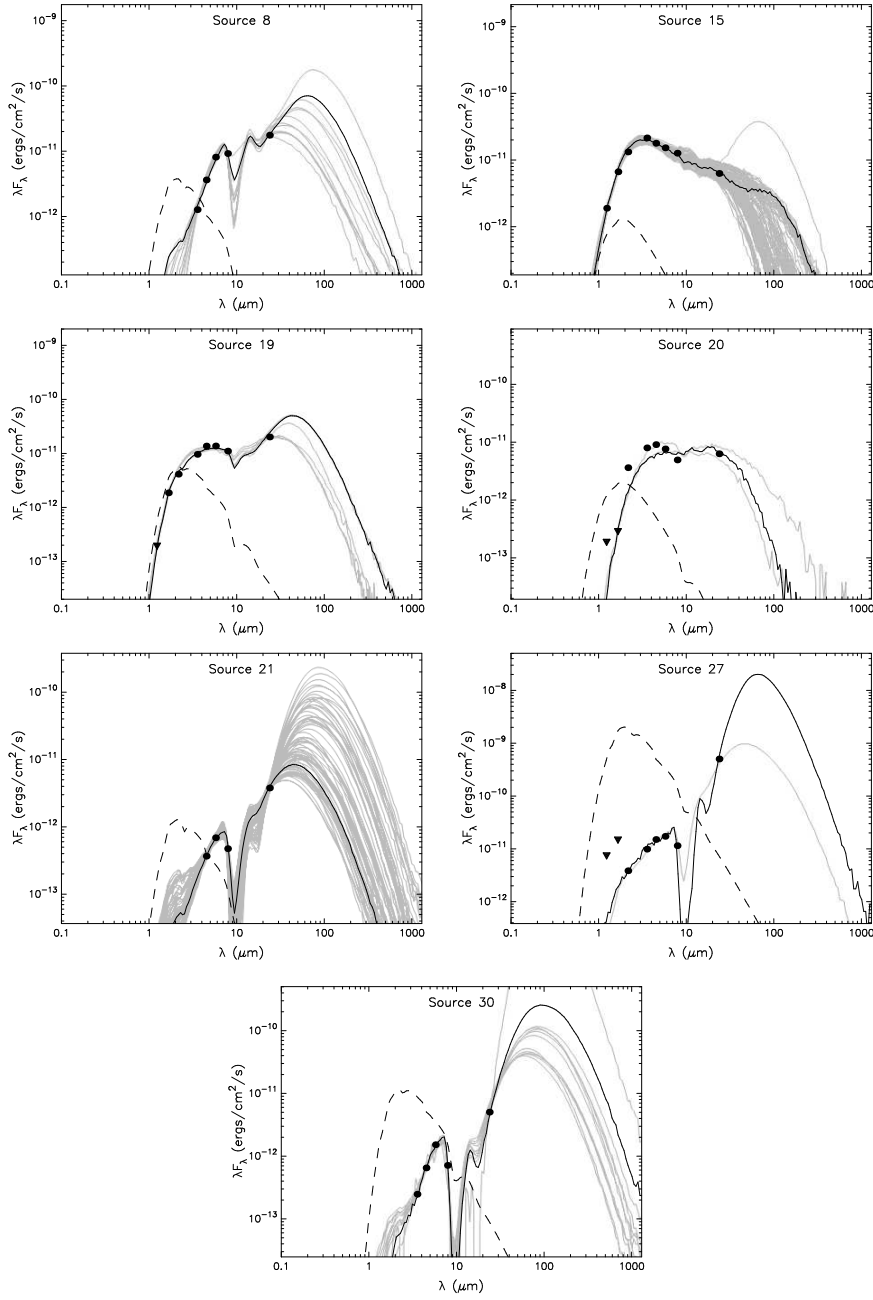
towards this region, which is about  $4 \times 10^{22} \text{ cm}^{-2}$ . This value was obtained from the HI column density derived from the VGPS HI data and from the  $\text{H}_2$  column density derived from the  $^{13}\text{CO}$  J=1–0 data.

The SED good fitting models are selected according to the following condition:  $\chi^2 - \chi_{\text{YSO}}^2 < 2N$ , where  $\chi_{\text{YSO}}^2$  is the  $\chi^2$  of the YSO best-fit model, and  $N$  is the number of input data fluxes (fluxes specified as upper limit do not contribute to  $N$ ). Hereafter, we refer to models satisfying the above equation as “selected models”. The fitting tool also fits the data to a stellar photosphere and defines the parameter  $\chi_\star^2$  to evaluate the goodness of the fitting. By making a comparison between  $\chi_{\text{YSO}}^2$  and  $\chi_\star^2$  we can confirm which sources are in fact YSOs and which sources may be stars externally reddened by the ISM. The SED fitting allows us to establish the evolutionary stage of the YSO candidates by considering the physical parameters of the sources: the central source mass  $M_\star$ , the disk mass  $M_{\text{disk}}$ , the envelope mass  $M_{\text{env}}$ , and the envelope accretion rate  $\dot{M}_{\text{env}}$ . According to Robitaille et al. (2006), stage I YSOs are those that have  $\dot{M}_{\text{env}}/M_\star > 10^{-6} \text{ yr}^{-1}$ , i.e., protostars with large accretion envelopes; stage II are those with  $M_{\text{disk}}/M_\star > 10^{-6}$  and  $\dot{M}_{\text{env}}/M_\star < 10^{-6} \text{ yr}^{-1}$ , i.e., young objects with prominent disks; and stage III are those with  $M_{\text{disk}}/M_\star < 10^{-6}$  and  $\dot{M}_{\text{env}}/M_\star < 10^{-6} \text{ yr}^{-1}$ , i.e., evolved sources where the flux is dominated by the central source.

**Table 3.** Parameters derived from the SED fitting of sources from which we obtained fluxes at  $24 \mu\text{m}$  from the MIPS image.

Source	$\chi_{\text{YSO}}^2/N$	$\chi_\star^2/N$	$n$	$M_\star$ ( $M_\odot$ )	$M_{\text{disk}}$ ( $M_\odot$ )	$M_{\text{env}}$ ( $M_\odot$ )	$\dot{M}_{\text{env}}$ ( $M_\odot/\text{yr}$ )	Stage
YSO 8	1	520	12	1 – 4	$1 \times 10^{-3} - 2 \times 10^{-1}$	$5 \times 10^{-8} - 3 \times 10^1$	$0 - 3 \times 10^{-4}$	I
YSO 15	0.4	50	109	3 – 5	$1 \times 10^{-5} - 1 \times 10^{-1}$	$6 \times 10^{-9} - 2$	$0 - 2 \times 10^{-7}$	II
YSO 19	1	> 9999	7	4	$3 \times 10^{-3} - 5 \times 10^{-2}$	$2 \times 10^{-4} - 8 \times 10^{-2}$	$0 - 9 \times 10^{-6}$	I, II
YSO 20	28	> 9999	1	5	$3 \times 10^{-4}$	$4 \times 10^{-6}$	0	II
YSO 21	0.1	505	72	0.2 – 5	$6 \times 10^{-4} - 3 \times 10^{-1}$	$9 \times 10^{-3} - 2 \times 10^2$	$2 \times 10^{-6} - 9 \times 10^{-4}$	I
YSO 30	1.5	580	12	2 – 13	$2 \times 10^{-3} - 5 \times 10^{-1}$	$2 - 5 \times 10^2$	$5 \times 10^{-5} - 6 \times 10^{-3}$	I
YSO 27	1.3	>9999	2	8 – 18	$0 - 4 \times 10^{-2}$	$7 \times 10^1 - 2 \times 10^2$	$8 \times 10^{-5} - 2 \times 10^{-3}$	I

In Table 3, we report the main results of the fitting output for the YSO candidates from which we obtained fluxes at  $24 \mu\text{m}$  from the MIPS image. In Col. 2 and 3 we report the  $\chi^2$  per data point of the YSO and stellar photosphere best-fit model, respectively, and in Col. 4 the number of models satisfying the  $\chi^2$  equation. The remaining columns report the physical parameters of the source, specifying the range of values of the selected models: central source mass, disk mass, envelope mass, and envelope accretion rate, respectively. Following the criteria of Robitaille et al. (2006), the last column indicates the evolutionary stage inferred from the inspection of the selected models. Figure 8 shows the SED of these sources. From this analysis can be appreciated that for source 15 the flux at the longer wavelengths comes mainly from the disk, indicating that it is a class II YSO, in coincidence with its position in the Spitzer-IRAC CC diagram. The SED for source 20 also shows the characteristics of a class II YSO. In the case of source 19 the selected models indicate that this source could be stage I and II. For sources 8, 21, 27, and 30 the selected models are stage I and the SED shows that the flux at the longer wavelengths is dominated by the envelope flux. These sources, together with source 19, are located in the region of class I YSO in the CC diagram (except for source 21 that lacks flux at  $3.6 \mu\text{m}$ ), confirming their youth.



**Fig. 8.** SED of sources from which we obtained fluxes at 24  $\mu\text{m}$  from the MIPS image. The sources are numbered according to Table 3 and Figs. 6 and 7. In each panel, black line shows the best fit, and the gray lines show subsequent good fits. The dashed line shows the stellar photosphere corresponding to the central source of the best fitting model, as it would look in the absence of circumstellar dust. The points are the input fluxes.

From Fig. 7 and the SED analysis we can confirm the presence of YSOs around G35.6. Thus, we conclude that the region is indeed active in star formation and we suggest that the birth of some of the YSOs, mainly those belonging to Group 1 and sources 27 and 28 could have been triggered by the expansion of the HII region G35.6. Most of the remaining intrinsically red sources belonging to Group 2, 3, and 4 may also be YSOs but their position far from the HII region does not allow us to confirm that their formation was triggered by G35.6.



## 8. Collect and collapse scenario

In order to determine if the collect and collapse mechanism is the responsible for the star formation that is taking place in the periphery of the HII region G35.6, we estimate and compare the age of the HII region and the fragmentation time predicted by the theoretical models of Whitworth et al. (1994a,b).

Using a simple model described by Dyson & Williams (1980) we calculate the age of the HII region at a given radius  $R$  as:

$$t(R) = \frac{4 R_s}{7 c_s} \left[ \left( \frac{R}{R_s} \right)^{7/4} - 1 \right],$$

where  $c_s$  is the sound velocity in the ionized gas ( $c_s=10 \text{ km s}^{-1}$ ) and  $R_s$  is the radius of the Strömgren sphere, given by  $R_s = (3N_{\text{uv}}/4\pi n_0^2 \alpha_B)^{1/3}$ , where  $\alpha_B=2.6 \times 10^{-13} \text{ cm}^3 \text{ s}^{-1}$  is the hydrogen recombination coefficient to all levels above the ground level.  $N_{\text{uv}}$  is the total number of ionizing photons per unit of time emitted by the star(s), and  $n_0$  is the original ambient density.

Taking into account the results of Sec. 6, we consider a Lyman continuum photon flux of  $1.0 \times 10^{48} \text{ ph s}^{-1}$ . Adopting a radius of  $\sim 1.5'$  for the HII region, a distance of 3.7 kpc, and an original ambient density of  $\sim (1 \pm 0.5) \times 10^3 \text{ cm}^{-3}$ , we derive a dynamical age between 0.18 and 0.35 Myr for G35.6. To coarsely estimate the original ambient density (assuming an error of 50%) we distributed the above calculated mass of the molecular shell,  $\sim 10^4 M_\odot$ , over an ellipsoid of revolution with semiaxes of 3 and 7 pc that encloses the molecular and ionized gas.

As analyzed in Sec. 5, the morphology of the molecular gas that encircles the HII region suggests that the expansion of G35.6 is collecting the gas at its periphery. Finally, we ask if the fragmentation of the collected layer of material can be taking place in the region. To answer it, we estimate when the fragmentation of the collected layer should occur according to the Whitworth's models. Assuming a turbulent velocity in the collected layer  $a_s$ , ranging between 0.2 and  $0.6 \text{ km s}^{-1}$  (Whitworth et al. 1994b), a Lyman continuum photon flux of  $1.0 \times 10^{48} \text{ ph s}^{-1}$ , and the previously estimated original ambient density of  $\sim (1 \pm 0.5) \times 10^3 \text{ cm}^{-3}$ , we find that the fragmentation process in the periphery of G35.6 should occur between 1.6 and 5.3 Myr after its formation, a time larger than the G35.6 dynamical age derived above. The range for the fragmentation time arises from considering the error in the original ambient density and the range in the turbulent velocity. Thus, we conclude that the formation of the YSOs lying at the border of the HII region most probably results from other processes, such as the radiative driven implosion (RDI) mechanism, which consists in interactions of the ionization front with pre-existing condensations (Lefloch & Lazareff 1994), or small-scale Jeans gravitational instabilities in the collected layer.

## 9. Summary

Using multiwavelength surveys and archival data, we studied the ISM towards the HII region G35.673-00.847 (G35.6). This work is part of a systematic study that we are performing with the aim to increase the observational evidence of triggered star formation in the surroundings of HII regions. The main results can be summarized as follows:

(a) The PAH emission around G35.6 seen at  $8 \mu\text{m}$  shows that the HII region has an almost semi-ring like shape with a cut towards the galactic west. The radius of this semi-ring is about  $1'.5$ . The  $24 \mu\text{m}$  emission reveals the presence of hot dust in the interior of the HII region.

(b) The radio continuum emission shows that towards the south of G35.6, also identified as NVSS 185929+020334, lies the radio source NVSS 185938+020012, probably another HII region. From the HI absorption analysis we conclude that both sources are located at the same distance, and from the central velocity of the related molecular gas, we estimate that the whole complex is at the kinematic distance of  $\sim 3.7$  kpc.

(c) Using the  $^{13}\text{CO}$   $J = 1-0$  transition we analyze the molecular gas around G35.6. We find a molecular shell composed by clumps distributed around the HII region, suggesting that its expansion is collecting the material. The molecular shell has a density of about  $10^4 \text{ cm}^{-3}$ .

(d) From a photometric study and a SED analysis we find several sources (YSO candidates) very likely embedded in the molecular shell.

(e) We give some indirect evidence suggesting the possible location and properties of the exciting star(s) of G35.6 and NVSS 185938+020012. In the case of G35.6, from the radio continuum flux, the near-IR photometry and the physical location of the analyzed sources, we find four candidates, likely O-type stars, to be the ionizing agent of the HII region. Among them, two are located close to the maximum of the  $24 \mu\text{m}$  emission, and one of them (our source #6) appears into a hole of  $5.8 \mu\text{m}$  emission, suggesting to be the most likely candidate. In the case of NVSS 185938+020012, we suggest that the exciting star(s) would be later than an O9.5V star.

(f) Analyzing the HII region G35.6 dynamical age and the fragmentation time of the molecular shell surrounding the HII region, we discard the collect and collapse as the mechanism responsible for the YSOs formation. We propose other possible processes of formation, such as radiative driven implosion and/or small-scale Jeans gravitational instabilities in the collected layer.

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